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X-ray flares, neutrino cooled disks, and the dynamics of late accretion in GRB engines

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ABSTRACT
We compute the average luminosity of X-ray flares as a function of time, for a sample of 10 long-duration gamma-ray burst afterglows. The mean luminosity, averaged over a timescale longer than the duration of the individual flares, declines as a power-law in time with index ~ -1.5. We elaborate on the properties of the central engine that can produce such a decline. Assuming that the engine is an accreting compact object, and for a standard conversion factor between accretion rate and jet luminosity, the switch between a neutrino-cooled thin disk and a non-cooled thick disk takes place at the transition from the prompt to the flaring phase. We discuss the implications of this coincidence under different scenarios for the powering of the GRB outflow. We also show that the interaction of the outflow with the envelope of the progenitor star cannot produce flares out of a continuous relativistic flow, and conclude that it is the dynamics of the disk or the jet-launching mechanism that generates an intrinsically unsteady outflow on timescales much longer than the dynamical timescale of the system. This is consistent with the fact that X-ray flares are observed in short-duration GRBs as well as in long-duration ones.

Key words: gamma-ray: bursts

1 INTRODUCTION

The *Swift* mission, with its ability to localize gamma-ray bursts (GRBs) in real time, has revolutionized our understanding of these phenomena in many ways. One of the most interesting discoveries is that the light curve of the X-ray afterglow displays a large diversity of behaviors (Nousek et al. 2006), rather than being a relatively featureless power-law.

The X-ray afterglow sets in as a rapidly fading source at the end of the prompt emission (Tagliaferri et al. 2005). This early phase is understood as the radiation of the prompt phase reaching the observer from off-axis angles $\theta \gg \Gamma^{-1}$ (Kumar & Panaitescu 2000; Kumar et al. 2006; Lazzati & Begelman 2006; Zhang et al. 2007). The steep decay phase is usually followed by a flat component, whose origin is still highly debated (Granot & Kumar 2006; Uhm & Beloborodov 2007; Genet et al. 2007; Ghisellini et al. 2007). Finally, at random times between a few hundred seconds up to several tens of thousands of seconds after the onset, the X-ray afterglow displays sudden rebrightenings, known as X-ray flares (Burrows et al. 2005; Falcone et al. 2006, 2007; Chincarini et al. 2007, hereafter C07). X-ray flares could be due to a variety of causes, either related to external shock activity or to the inner engine itself. It can be shown that any mechanism related to the external shock would produce flares with a characteristically long timescale (Lazzati et al. 2002; Lazzati & Perna 2007). Most of the observed flares have fast rise and decay times (C07; Kocevski, Butler & Bloom 2007) and must therefore be related to activity of the central engine at times comparable to those at which the flare is observed. For this reason, they are of great importance for our understanding of the mechanism that powers the GRB outflows. They are potentially unique laboratories to investigate the properties of relativistic outflows from compact objects over a broad range of luminosities. As we will see in the following, the isotropic equivalent luminosity of the outflow ranges from $\sim 10^{53}$ erg/s during the prompt phase to $\sim 10^{47}$ erg/s during flares at late times.

We study a sample of GRBs with X-ray flares that have been observed by the Swift X-ray Telescope (XRT) for a sufficiently long time and for which redshift information is available. We compute the average energy output from the inner engine as a function of the time elapsed since the GRB explosion, and we compare it to several mechanisms for energy extraction from a magnetar or a black hole.

This letter is organized as follows: in § 2 we discuss the sample and the procedure used to derive the cumulative light curve, in § 3 we discuss different mechanisms that could power the flares, in § 4 we discuss the role of the progenitor star in shaping the late time outflow, and in § 5 we discuss our results, their limitations and their implications.

GRB	z	$N_{\rm Flares}$	$T_{\rm max}$ (s)
050724	0.258	3	3.4×10^5
050730	3.967	4	9.9×10^4
050802	1.71	1	3.0×10^5
050814	5.3	2	1.1×10^5
050820a	2.612	1	1.1×10^6
050904	6.29	7	4.3×10^4
050908	3.344	2	2.8×10^4
051016b	0.9364	1	6.9×10^5
060115	3.53	1	7.9×10^4
060124	2.296	2	6.3×10^5

Table 1. Properties of the bursts selected for the analysis

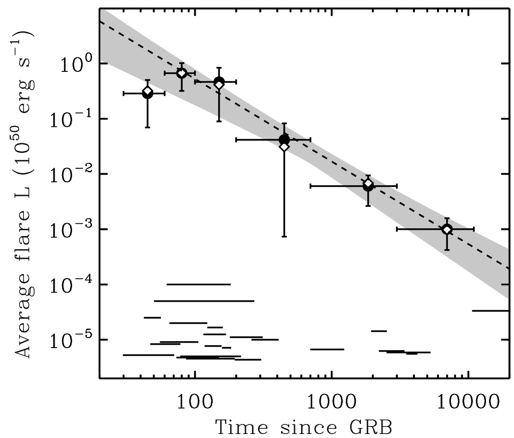

Figure 1. Average flare light curve of the subsample of *Swift* afterglows that show flaring activity and for which a redshift has been measured. The dashed line shows the best power-law fit, while the shaded area shows the 1σ confidence region of the slope and normalization. The white lozenges show the result obtained by using the power-law fluences in F07 rather than the Band ones. The horizontal lines in the bottom of the plot show the times at which flares have been observed. Their ordinate is arbitrary.

2 DATA ANALYSIS AND RESULTS

We selected from the tables in Falcone et al. (2007; hereafter F07) the sub-sample of bursts with X-ray flares for which redshift information is available. The bursts and some of their key properties are listed in Tab. 1. The sample consists of 10 GRBs for a total of 24 flares. All the bursts have XRT observations up to comoving time $t \sim 3 \times 10^4$ s.

The flare isotropic equivalent energy was computed from the fluence $\mathcal{F}$ in Tab. 6 of F07. The average flare light curve between the times t_1 and t_2 was computed as:

$$\langle L \rangle_{t_1,t_2} = \frac{1}{n_{\rm GRB}} \sum_{i=1}^{n_f} L_i \, \delta t_{i,1,2} \qquad , \tag{1}$$

where L_i is the average luminosity of the i^{th} flare during its active time, $n_{\rm GRB} = 10$ is the total number of GRBs considered, $n_f = 24$ is the total number of flares and $0 \le \delta t_{i,1,2} \le 1$ is the fraction of time in the interval (t_1, t_2) during which the $i^{\rm th}$ flare is active. This prescription is equivalent to the assumption that the flares have a square shape. Even though this is a very poor approximation to the real shape of the flares, its effect is negligible when many flares are averaged to compute the light curve. We tested both a Gaussian shape (C07) and a triangular shape, and we obtained consistent results within the errors.

The computation of the errors in the average light curve is nontrivial, since the main contribution is not the uncertainty in each fluence measurement, but rather the uncertainty in the number of flares that are observed on average during a given time interval. For this reason we assume that the uncertainty of each fluence is as large as the measurement itself and we compute the errors on the average light curve as:

$$\sigma_{\langle L \rangle_{t_1,t_2}} = \frac{1}{n_{\rm GRB}} \left[\sum_{i=1}^{n_f} \left(L_i \, \delta t_{i,1,2} \right)^2 \right]^{1/2} . \tag{2}$$

This prescription ensures that if the average flux at a certain time is dominated by a single bright flare, the error is large. Small errors occur only in time intervals with a large number of flares.

The resulting light curve is shown in Fig. 1, where $\langle L \rangle_{t_1,t_2}$ is shown versus time ($t = (t_2 - t_1)/2$). The solid dark points with error bars show the results assuming a Band model spectrum for the flares (Band et al. 1993; F07), while the white lozenges show the results of the power-law spectral model (F07). We model the average light-curve as a power-law, excluding the first point (at $t \sim 40$ s) since it is still contaminated by the prompt emission in many cases. We find that the average light curve is very well described by a power-law with index (1σ errors):

$$\alpha = -1.5 \pm 0.16 \, . \tag{3}$$

The fit has χ^2/d.o.f.= 0.2, a small value that is not surprising given the very conservative assumptions on the uncertainties. The formal error of 0.16 is, as a consequence, very conservative. In order to check the result, we computed the average light curve also as the derivative of the cumulative energy produced as a function of time since the GRB onset, finding analogous results.

Averaging many bursts together allowed us to increase the signal-to-noise ratio of the flare light curve. We now examine whether the resulting slope can be recovered in individual GRBs that display a large number of flares. When we compute the flare light curve for an individual event, the knowledge of the redshift is not necessary and we can select the GRBs from a larger pool of events. There are three GRBs in the F07 catalog with six or more flares. One is GRB 050904, which is in our sample and has 7 flares. Another is GRB 051117a, which has 7 flares according to F07. However, the seven flares of GRB 051117a overlap one another and therefore we discard this event from our analysis. Finally, GRB 050803 has six flares.

Figure 2 shows the flare light curve, in observed time and flux, for these two bursts. Power-law fits were performed for these cases, yielding $\alpha = -1 \pm 0.4$ and $\alpha = -1 \pm 0.3$ for GRB 050803 and GRB 050904, respectively. Even though the uncertainties are larger, as expected given the smaller statistics, the individual cases confirm that flares produce more luminosity at early times than at late times, their light curve is consistent with a power-law, and the index of the power-law is consistent with the cumulative curve of Fig. 1.

GRB 050904 has seven flares and is also part of our main sample. Since it has so many flares, we checked that the results for the average flare energy are not dependent

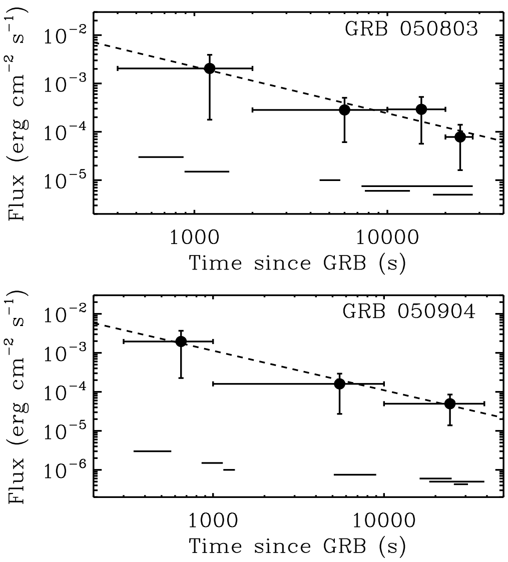

Figure 2. Flare light curve for GRB 050803 (upper panel) and GRB 050904 (lower panel). The meaning of symbols is analogous to Fig. 1.

on the presence of GRB 050904 in the sample. Reproducing Fig. 1 without the seven flares of GRB 050904 yields similar results, with a slope $\alpha = -1.8 \pm 0.3$, in agreement with the result of Eq. 3.

3 POWERING MODES

Even though collimated outflows originating from compact objects accreting matter from a disk are ubiquitous in the universe (e.g., Ferrari 1998; Blandford 2001), the actual mechanism that produces the jet and determines its properties (luminosity, entropy, opening angle, structure, and magnetization) remains elusive. In addition, we see jets in other types of objects, such as pulsars, where mechanisms other than accretion could play a role in the jet production (but see Blackman & Perna 2004). In the case of GRBs, several mechanisms have been proposed to produce the relativistic jet: conversion of internal energy into bulk motion with hydrodynamic collimation (Cavallo & Rees 1978; Lazzati & Begelman 2005), energy deposition from neutrinos, energy released from a rapidly spinning, newly born magnetar (Usov 1992), and magnetic collimation and acceleration (Vlahakis & Königl 2001). It has proven so far extremely challenging to prune some of these possibilities, since the GRB radiation is produced far away from the place where the outflow is accelerated, and we have not been able to connect the properties of the radiation (light curves and spectra) to the (magneto)-hydrodynamical properties of the plasma producing it.

Let us first consider a system made by a newly formed stellar mass black hole accreting matter at a high rate from a disk. During the prompt GRB phase, such a disk is so hot and dense that neutrino losses provide an effective cooling mechanism (Popham, Woosley & Fryer 1999; Narayan, Piran & Kumar 2001; Chen & Beloborodov 2007). In this phase, the jet may be powered by neutrino annihilation, even though magnetic effects could play a dominant role. In the latter case, the outflow may either originate on the disk surface, as material escapes along low inclination magnetic field lines (e.g., Levinson 2006), or by Blandford-Znajek mechanisms (e.g., McKinney & Gammie 2004). 1D steady-state calculations of Chen and Beloborodov (2007) showed that, for a rotating BH, the switch from a neutrino-cooled to an advective disk takes place at an accretion rate of $10^{-3} - 10^{-2} M_\odot$/s, depending on the viscosity prescription used. In all cases, the switch-off of the neutrino cooling is expected to be associated to a change in the GRB outflow characteristics, since the magnetic field that can be anchored to a dense, high pressure, thin disk is expected to be stronger than the one anchored to a lower-density, lower-pressure, thick inflow.

Figure 3 shows the average flare luminosities in units of the accretion rate in solar masses per second, where we assumed that the GRB is beamed into 1 per cent of the sky, that the efficiency of converting the accretion rate into jet luminosity is 0.1 per cent, and that these two parameters are constant. The two parameters are rather standard (e.g., Chen & Beloborodov 2007; Podsiadlowski et al. 2004). Changing them by a factor up to ten would not affect the main conclusion since the prompt and flare luminosities would scale in the same way. The average luminosity of the prompt phase of the 10 GRBs is also shown in the figure with a thick solid line. Such accretion rates are compared to the one at which neutrino cooling is switching on/off (Chen & Beloborodov 2007). This transition lies suggestively at the boundary between the prompt phase and the flaring phase. We argue that this could be an indication of the fact that the prompt phase of GRBs, the most luminous one, is powered by accretion onto a black hole in the form of a geometrically thin – neutrino cooled – disk. As the accretion rate drops under the critical value, the fast accretion is switched off and the prompt phase ends. The disk swells under the effect of internal pressure and a new accretion geometry, with a thick disk, sets in. This gives rise to the flares that we observe during the afterglow phase.

In the case of a magnetically driven jet, the change in the outflow dynamics would be brought about by the fact that a thick disk has a lower pressure and therefore can anchor a magnetic field with lower intensity. It would also change the pitch angle of low-inclination magnetic field lines. In the case of a neutrino powered outflow, the switch off of the neutrino cooling would shut off completely the outflow. It seems therefore that the observations of late-time, low-luminosity flares provide evidence against the powering of GRB outflows exclusively by neutrino annihilation.

The material necessary to provide the accretion at late stages can be provided, in long-duration gamma-ray bursts, by the fallback of material that did not reach the escape velocity in the stellar explosion (Chevalier 1989; MacFadyen, Woosley & Heger 2001; Zhang & Woosley 2008). Alternatively, especially in the case of short GRBs, the natural evolution of an accretion disk can supply the accretion rate necessary to explain the observations. Consider an accretion disk that forms in a short timescale (comparable to or smaller than the duration of the GRB prompt phase) and is left to evolve without any sizable mass input thereafter. The accretion rate depends on the assumptions made on the nature of viscosity. The case of a thin disk has been studied thoroughly. Frank, King & Raine (2002) report the exact

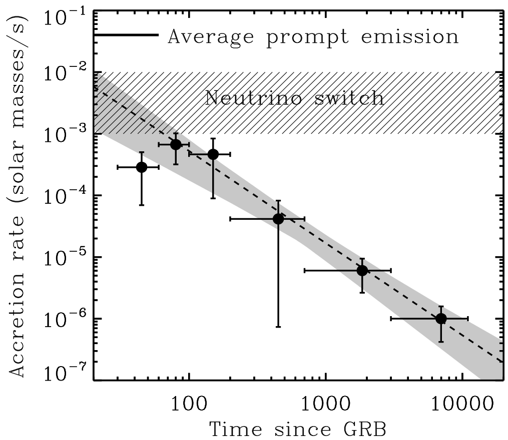

Figure 3. Accretion rate (in solar masses per second) as a function of time during the flaring phase. A GRB beaming factor of 1 per cent and an accretion efficiency of 0.1 per cent have been assumed. The average accretion rate during the prompt phase is also shown. The hatched area shows the region where the neutrino cooling is supposed to turn off (Chen & Beloborodov 2007). It suggestively lies between the prompt and the flare accretion rates.

solution for the case of a thin disk with constant viscosity. They show that, after several tens of viscous time-scales, the accretion rate onto the central object approaches the asymptotic form $\dot{m} \propto t^{-1.25}$. Cannizzo, Lee & Goodman (1990) performed numerical simulations for the same initial conditions using the prescriptions of α-viscosity (Shakura & Sunyaev 1973). They find that the accretion rate at late times scales with time as $\dot{m} \propto t^{-1.2}$, independently of the value of α_ν assumed. The case of a thick disk needs to be studied in detail (Lazzati & Begelman in preparation). The comparison of the observed flare luminosity to the theoretical rates of late-time accretion implies that there is an almost linear relation between accretion and the luminosity of the outflow. In our favored scenario, where the outflow is powered by magnetic processes, this relation would be caused by the decay of the magnetic field as the disk becomes less massive and dense. The reason why we observe such a linear relation is not entirely clear and deserves further investigation.

An alternative to the accretion disk–BH system is a rapidly spinning magnetar that powers the outflow as a consequence of spin-down (Thompson, Chang & Quataert 2004; Bucciantini et al. 2008). This system can provide late-time energy either through neutrino emission or through dipole radiation. The neutrino emission decays exponentially and cannot provide the power required (Thompson et al. 2004). In the simple vacuum dipole scenario the decay of the late-time energy deposition is too steep ($L \propto t^{-2}$). However, the interaction of the field with the stellar material can create shallower slopes consistent with the observations. In this scenario, the fact that the neutrino cooling switch coincides with the transition from the prompt to the flaring phase is purely coincidental. In addition, it is not clear how the continuous luminosity produced by the spin-down of the magnetar can be converted into a flaring source.

4 FROM STEADY STATE TO IMPULSIVE

Even though the average flare curve of Fig. 1 is featureless, we ought to keep in mind that flares are episodic events. The fact that an accretion disk or a spinning magnetar can provide energy at late time does not ensure that the energy will be released intermittently. It is not surprising to observe variability of relativistic sources on timescales comparable to the dynamical time of the system. However, in the case of flares, the variability timescale is many orders of magnitude longer than the dynamical one for a solar mass black hole, and it grows approximately linearly with time (C07). It is more likely that this variability is associated to a viscous time-scale rather than to the dynamical time scale. We must therefore seek either a mechanism that can release energy episodically from the inner engine, or a way to transform a continuous output of energy into a highly variable one as it propagates from the engine to the radiation zone.

The propagation of the jet through the cold stellar progenitor material provides in principle a way by which a continuous outflow can be converted into a succession of individual fireballs. Morsony et al. (2007) showed that even if a continuous jet is injected into the core of a massive star, the ensuing light curve is highly variable. Consider an engine releasing an outflow with continuous but decreasing luminosity. Inside the star the jet is in pressure equilibrium with a high pressure cocoon of material (Lazzati & Begelman 2005). As the jet luminosity decreases, the cocoon becomes over-pressured and squeezes the jet. At the same time, the cocoon pressure decreases due to the fact that the cocoon material is escaping from the surface of the star. If, at any point in time, the cocoon pressure overcomes the stagnation pressure of the jet, the jet would be choked and the flow of energy interrupted.

The stagnation pressure of a relativistic outflow with Lorentz factor Γ and cross section Σ is given by $p_{\rm stag} = L_j\,\Gamma^2/(4c\Sigma)$, where L_j is the luminosity of the jet. Following Lazzati & Begelman (2005), the cocoon pressure can be written as:

$$p_{\rm cocoon} = \left(\frac{L_{\{j,0\}}\rho_\star}{3\,r_\star\,t_{\rm br}}\right)^{1/2} e^{-\frac{c\,t}{\sqrt{3}\,r_\star}} \qquad (4)$$

where $L_{\{j,0\}}$ is the average jet luminosity before breakout, $\rho_\star$ is the average stellar progenitor density and $r_\star$ its radius, and $t_{\rm br}$ is the breakout time.

A condition for the stagnation of the jet can be obtained by comparing the stagnation pressure with Eq. 4. It can be seen that the cocoon pressure cannot reach the jet stagnation pressure for any reasonable parameter set. We conclude therefore that the instability giving rise to the flaring behavior of the late time activity of the inner engine has to be intrinsic to the jet release process or to its transition from the non-relativistic to the relativistic stage, and cannot be brought about by the propagation of the relativistic outflow in the star.

5 DISCUSSION AND CONCLUSIONS

We have computed the average energy released in the form of X-ray flares overlaid on the power-law decay of the afterglow of long-duration gamma-ray bursts. A sample of 10 long

duration GRBs from the catalog of F07 with redshift measurements was used for the analysis. We conclude that, on average, the late-time energy release approximately follows the power-law scaling $L \propto t^{-1.5}$. Our analysis is possibly affected by several biases. First, the definition of a flare is fraught with uncertainty, as the comparison of the C07 and the F07 catalogs easily reveals. We here adopt the definition of F07 and refer to that paper for a discussion of their selection criteria. Second, the measurement of the slope of the power-law depends on our capability to select flares. Low brightness flares could be lost in the early phases when the afterglow can easily outshine them. On the other hand, very short duration flares could be missed at late times when the observations are not continuous in time. It appears that the first bias is most serious (since no very short duration flare was ever detected in the late phases) and that the slope is possibly underestimated. We do not believe this should affect our conclusions, since almost all the GRBs we considered have an early flare and so the contribution of shallow flares would be minimal. One important effect could, however, create a systematic overestimation of the slope. The late time flares may be less beamed than the early ones, and therefore their isotropic equivalent luminosities would appear smaller than the one of early flares due, in part, to geometric end not intrinsic effects. According to simulations, however, most of the opening angle evolution takes place at very early times (Morsony et al. 2007), as long as the injection opening angle does not evolve.

The energy to power the flares may come from accretion or from the spinning down of a magnetar. In the first case, we were able to estimate the accretion rate required to power the prompt emission as well as the flaring phase. Interestingly, during the prompt phase the accretion rate is so large that neutrino emission cools the flow and accretion takes place in the form of a thin disk. At accretion rates of about 0.001 to 0.01 solar masses per year, the neutrino luminosity drops and the accretion disk becomes thick. We find that the switch-off of the neutrino cooling, and the transition from a thin to a thick disk, take place between the prompt and the flaring phase. Indeed, the prompt emission spikes and the late-time flares exhibit some differences. While the prompt spikes do not show any evolution in their duration or peak luminosity, the flares become longer and shallower with time. This property naturally arises in a disk that fragments and accretes the various blobs of material on their viscous timescales (Perna, Armitage & Zhang 2006). In addition, flares are very episodic and the engine is "off" most of the time at late stages, while during the prompt phase the engine is "on" most of the time. We propose that the differences are due to the switch from a thin disk to a thick disk configuration. A more detailed analysis of the thick disk accretion dynamics is on-going (Lazzati & Begelman in preparation).

An alternative scenario is that of a spinning-down pulsar. In this case, the fact that the neutrino switch coincides with the transition from the prompt to the flare phase would be a pure coincidence. More observations and a better understanding of both engine models are needed before definitive conclusions can be drawn. Although we have focused on long-duration GRBs in this paper, from a theoretical point of view short-duration GRBs may also have a flaring phase, as long as they are powered by accretion from a disk or by the spin-down of a magnetar. The late-time accretion provided by a disk that is draining into the BH is sufficient to power the flares independently of the presence or not of fall-back material from the progenitor star.

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REFERENCES

Band D., et al., 1993, ApJ, 413, 281
Blackman, E. G., Perna, R. 2004, ApJ, 601, L71
Blandford R. D., 2001, Progress of Theoretical Physics Supplement, 143, 182
Bucciantini N., Quataert E., Arons J., Metzger B. D., Thompson T. A., 2008, MNRAS, 383, L25
Burrows D. N., et al., 2005, Sci, 309, 1833
Cannizzo J. K., Lee H. M., Goodman J., 1990, ApJ, 351, 38
Cavallo G., Rees M. J., 1978, MNRAS, 183, 359
Chen W.-X., Beloborodov A. M., 2007, ApJ, 657, 383
Chevalier R. A., 1989, ApJ, 346, 847
Chincarini G., et al., 2007, ApJ, 671, 1903 (C07)
Falcone A. D., et al., 2006, ApJ, 641, 1010
Falcone A. D., et al., 2007, ApJ, 671, 1921 (F07)
Ferrari A., 1998, ARA&A, 36, 539
Frank J., King A., Raine D. J., 2002, "Accretion Power in Astrophysics", Cambridge University Press, Cambridge, UK
Genet F., Daigne F., Mochkovitch R., 2007, MNRAS, 381, 732
Ghisellini G., Ghirlanda G., Nava L., Firmani C., 2007, ApJ, 658, L75
Granot J., Kumar P., 2006, MNRAS, 366, L13
Kocevski D., Butler N., Bloom J. S., 2007, ApJ, 667, 1024
Kumar P., Panaitescu A., 2000, ApJ, 541, L51
Kumar P., McMahon E., Barthelmy S. D., Burrows D., Gehrels N., Goad M., Nousek J., Tagliaferri G., 2006, MNRAS, 367, L52
Lazzati D., Rossi E., Covino S., Ghisellini G., Malesani D., 2002, A&A, 396, L51
Lazzati D., Begelman M. C., 2005, ApJ, 629, 903
Lazzati D., Begelman M. C., 2006, ApJ, 641, 972
Lazzati D., Perna R., 2007, MNRAS, 375, L46
Levinson A., 2006, ApJ, 648, 510
MacFadyen A. I., Woosley S. E., Heger A., 2001, ApJ, 550, 410
McKinney J. C., Gammie C. F., 2004, ApJ, 611, 977
Morsony B. J., Lazzati D., Begelman M. C., 2007, ApJ, 665, 569
Nousek J. A., et al., 2006, ApJ, 642, 389
Perna, R., Armitage, P. J., Zhang, B, 2006, ApJ, 636, L29
Podsiadlowski P., Mazzali P. A., Nomoto K., Lazzati D., Cappellaro E., 2004, ApJ, 607, L17
Popham R., Woosley S. E., Fryer C., 1999, ApJ, 518, 356
Shakura N. I., Syunyaev R. A., 1973, A&A, 24, 337
Tagliaferri G., et al., 2005, Nature, 436, 985
Thompson T. A., Chang P., Quataert E., 2004, ApJ, 611, 380
Uhm Z. L., Beloborodov A. M., 2007, ApJ, 665, L93
Usov V. V., 1992, Nature, 357, 472
Vlahakis N., Königl A., 2001, ApJ, 563, L129
Zhang B.-B., Liang E.-W., Zhang B., 2007, ApJ, 666, 1002
Zhang W., Woosley S. E., Heger A., 2008, ApJ in press (arXiv:astro-ph/0701083v2)